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Coriolis Effects During Pitch and Roll Maneuvers In a Piloted Flight Simulator

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The purpose of this study was to determine the effects of suprathreshold values of Coriolis acceleration on the pilot of a flight simulator with particular reference to his perception of illusory motion and his position in space. The particular Coriolis stimuli selected were those that would be anticipated in the use of the Ames five-degrees-of-freedom simulator in studies of aircraft and spacecraft. Three modes of simulator motion were used: rotation of the cockpit around the z axis at 30 feet from the center of rotation, and pitch and roll of the cockpit. The data consisted of subjective reports of apparent motion and estimates of body position. Seven experienced observers who showed normal post-acceleration and post-deceleration after effects of rotation on the simulator were used. Two were research pilots, and the others were the authors and three members of the Ames staff.

The frequency of reports of Coriolis effects increased as a function of simulator velocity from 2 to 12 rpm for both pitch and roll maneuvers. The frequency of the Coriolis effects was nearly 100 per cent at 7 rpm and above. The duration of the Coriolis effects also increased as a function of the simulator velocity, the duration of the effects for pitch and roll being very similar. The mean duration of the reported rotation was approximately 9 seconds at 2 rpm and 15 seconds at 12 rpm, for the pitch and roll maneuvers used.

The observers' estimate of body position tended to be very close to the deviation of his body position from the direction of the resultant force acting on him under the various experimental conditions. The observers did, however, tend to underestimate the variation of their body position at the lower velocities in accordance with similar static estimates, but they tended to be close to the corresponding angle at 12 rpm.

WHEN A HUMAN riding on a rotating device tilts his head about an axis other than that of the axis of rotation, he experiences apparent motion which is dependent on the direction and velocity of rotation.[6,7] Such effects have been known for many years and have become of special interest with respect to rotating space platforms. Similarly, the pilot of a rotating flight simulator will experience such effects when he rotates the cockpit about an axis other than the axis of rotation. These motions, however, have a much longer duration than the typical head movements. Whereas the head movements require from approximately 0.2 to 0.6 seconds,[6] cockpit rotation may require several seconds with correspondingly different effects.[5,7] The apparent body motions caused by these conditions have been termed Coriolis effects and are the result of Coriolis couples acting on the semicircular canals.[6] The term Coriolis effect will, therefore, be used in this paper to refer to the observers' perception of *apparent* bodily rotation in planes other than the plane of cockpit motion during the rotation of the simulator.

The specific purpose of this study was to determine the effects of suprathreshold values of Coriolis acceleration on the pilot of a flight simulator with particular reference to his perception of illusory motion and his perception of his position in space. The particular Coriolis stimuli selected were those which would be anticipated in the use of the Ames five-degrees-of-freedom simulator in studies of hypersonic aircraft and of the control of space vehicles. The study was designed to obtain data on three basic variables: (1) perception of apparent cockpit rotation, (2) changes in apparent cockpit position, and (3) motion sickness.

METHOD

Apparatus.—The Ames five-degrees-of-freedom simulator was used to rotate the observers. This flight simulator (Fig. 1) is controlled by an electronic computer,

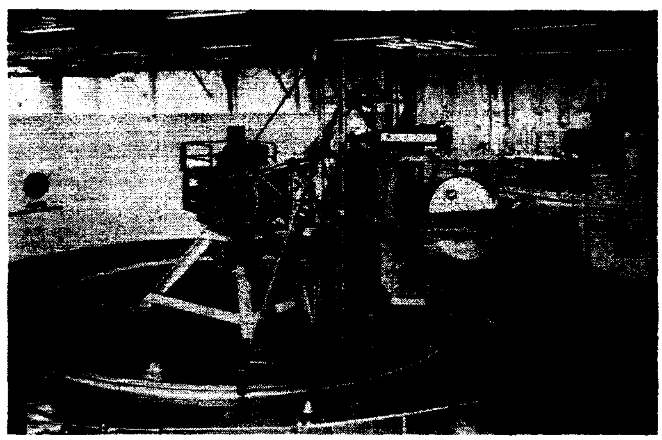

Fig. 1. The Ames five-degrees-of-freedom simulator.

and although it is capable of moving with five degrees of freedom, only three variables of motion were used: rotation of the cockpit about the z axis 30′ from the center of rotation and pitch and roll of the cockpit itself which produced the Coriolis accelerations. The cockpit was covered with an opaque hood and contained standard aircraft instruments, but these were not used. The observer was held firmly in position in the form fitting seat by means of shoulder harness and lap belt, and his feet were clamped in position. The observer wore a crash helmet which fitted firmly into a

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TABLE I. MAGNITUDE AND DEVIATION FROM THE VERTICAL OF THE RESULTANT ACCELERATION AT THE OBSERVERS HEAD

Cockpit position rpm	Magnitude, "g" units					Deviation from the vertical, deg.				
	-20°	-10°	0	10°	20°	-20°	-10°	0°	10°	20°
2	1.0008	1.00082	1.00085	1.00086	1.00087	2.30°	2.32°	2.35°	2.37°	2.39°
3	1.0042	1.0043	1.0044	1.0045	1.0045+	5.25°	5.32°	5.37°	5.42°	5.45°
5	1.032	1.0328	1.0333	1.034	1.0345	14.32°	14.47°	14.58°	14.73°	14.85°
7	1.119	1.121	1.123	1.125	1.127	26.62°	26.85°	27.07°	27.30°	27.47°
10	1.422	1.432	1.439	1.446	1.475	45.32°	45.70°	45.95°	46.23°	46.75°
12	1.777	1.792	1.803	1.817	1.824	60.6°	60.85°	61.0°	61.1°	61.25°

U-shaped head rest to minimize the muscular effort necessary to hold the head in position. Voice communication was available between the observer, the simulator operator, and the experimenter who operated the computer. The electromechanical drive system and its tie-in with the computer have been described elsewhere.[1]

Motions of the simulator were recorded by instrumentation similar to that used for other simulator studies as follows: (1) potentiometers for gimbal position, (2) calibrated tachometer for simulator velocity, (3) linear and angular accelerometers for linear and gimbal accelerations, and (4) rate gyros for gimbal velocities. The instrument signals were recorded on ink writing recorders for each observation. A typical time history of a trial in roll at 3 rpm is presented in Figure 2. One important feature to be noted is the recording of a pitching acceleration when only a roll motion was involved. Since the accelerometer used in these studies consists essentially of a torsion pendulum, this pitching acceleration resulted from a Coriolis couple acting on the accelerometer in a manner similar to that which occurs in the semicircular canals. This acceleration provides confusing motion cues in situations requiring combined simulator and gimbal motion.

The simulator has two characteristics which complicate the cues presented to the subject. The first involves the rise time for the velocity of the gimbals which is relatively long (Fig. 2). The gimbal motions are consistent, however, and for this study are described by a peak velocity and a duration. The stimulus duration is defined as the time from the initiation of motion to the time where the gimbal velocity falls to 5 per cent of the peak value. Another complicating motion cue results from the rotation of the simulator around the track. Track roughness causes vibratory accelerations at relatively high frequencies which varied for this study from ±0.03 g at 2 rpm to ±0.08 g at 12 rpm.

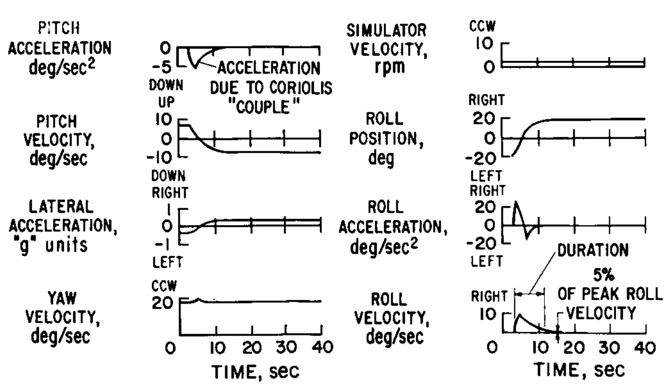


Fig. 2. A typical time history of a trial to determine the effects of Coriolis acceleration (3 rpm).

Since gimbal rotations on the simulator rotate the observer about his approximate center of gravity (very close to the belt buckle) rather than his head, the resultant acceleration acting on his vestibular end organs varies not only with simulator velocity but with gimbal position and may affect his estimate of body position. This variation in magnitude and direction of the resultant acceleration is presented in Table I.

Observers—Seven observers who showed normal post-acceleration and post-deceleration after effects of rotation on the simulator were used. Two were research pilots, and the others were the authors and three members of the Ames staff. All of the observers had had considerable experience in making observations in aircraft and/or rotating devices, and all were familiar with the problem under investigation.

Procedure—The observer sat facing the center of rotation, and the centrifuge rotated to his right (i.e., counterclockwise as viewed from above) during all of the observations. His task was to report on the following: (1) his perception of apparent bodily rotation throughout each trial, (2) his apparent body position before, during, and after each trial, and (3) any feeling of discomfort, motion sickness, or "stomach awareness." The following four variables of simulator motion were studied: (1) six simulator velocities (2, 3, 5, 7, 10, 12 rpm), (2) four gimbal directions (pitch-up and -down and roll right and left), (3) duration of motion (approximately 6-11 seconds), and (4) two gimbal excursions (20° and 40°). The first of the cockpit rotations began 10° from the vertical and ended 10° from the vertical in the opposite direction, while the second began 20° from the vertical and ended 20° from the vertical in the opposite direction (Fig. 2).

Each experimental trial began by tilting the observer to the position required for that trial. The simulator was then accelerated to the appropriate velocity and maintained at this speed throughout the trial. When the simulator had been rotating at a constant velocity for at least 30 seconds, or until the after effects of acceleration had disappeared, whichever was longer, the observer was asked to report his apparent bodily position with respect to gravity. The cockpit was then tilted 20° or 40° to produce the Coriolis acceleration, and the observer gave a running account of his perception of his body position and motion to the experimenter who recorded the nature and the duration of the effects. After 30 seconds or following the termination of the perception of apparent motion and other effects, whichever was longer, the observer was again asked to report on his perception of the position of his body with respect to gravity. Immediately thereafter, the cockpit was rotated back to its original position, and data were collected as during the first trial. Following the second trial, the velocity of the simulator was increased or decreased to the next speed which was maintained at a constant value for 30 seconds before the third trial was begun. This procedure was continued until 24 such trials were run in a 25-40 minute session. Four trials were taken for each condition for each observer. One trial for each condition for each observer was taken before a second trial for any condition was run.

Two different practice sessions preceded the data sessions to acquaint the observers with the observations and reports of motion and position they would be required to make. The first of these consisted of a special series of 28 trials for the 40° gimbal excursions in pitch and roll. This series presented at least one trial for each simulator velocity and direction of gimbal motion. During these trials the observers were also asked to note the post-acceleration and post-deceleration after effects to assist them in recognizing the motion sensations involved in this study as well as the time when these after effects had died out. All of the observers were reporting the effects directly and without difficulty at the end of these practice sessions.

The second type of practice session was used to give the observers some experience in estimating their body position. Initially the cockpit was placed in various positions and the observers were told their position. Following these trials, the cockpit was placed in the appropriate position, and the observer was asked to estimate this position. The positions were selected in a random order, and the test position was reached through a series of random movements. The cockpit was covered and the observers' eyes were closed during all observations.

Occasionally malfunctions occured in the simulator or computer causing the simulator to stop. In most cases the malfunction was momentary or could be corrected in a few seconds and the simulator restarted. The simulator would then be brought to the condition from which it had stopped and the series of trials completed when the post-acceleration effects had disappeared.

RESULTS

The results obtained during the rotation of the simulator will be described under two major categories: (1) the observer's perception of the apparent rotation of the cockpit and his body during and immediately following the pitching and rolling of the cockpit, that is, Coriolis effects, and (2) the observer's reports of his apparent body position immediately following each maneuver. With regard to the Coriolis effects it should be noted that the observer's force environment was very complex. First, the pitch or roll of the cockpit itself produced an angular acceleration followed shortly by a deceleration. The effects of these accelerations could be expected to be short lived because of the interference of each on the other[3] (Fig. 2). Secondly, there were the Coriolis couples produced by the pitch and roll of the cockpit while the simulator rotated. These stimulated the semicircular canals in planes other than those of the physical rotation of the cockpit and resulted in corresponding apparent motion of the cockpit. Thirdly, there were changes in the direction of resultant force acting on the body associated with the pitch or roll maneuver. These changes produced effects on the otolith organs and on other gravitational receptors. It is suggested, however, that the primary effects were associated with the Coriolis couples affecting the semicircular canals. These effects would themselves appear to be complex since the pitch and roll of the cockpit did not produce completely uniform perception of apparent rotation for the different observers nor even with the same observer on successive trials under a single condition.[5]

A. *Coriolis effects.*

1. *Frequency of Coriolis effects*—For some observers the Coriolis effect was a simple apparent motion in a single plane other than the plane of the rotation of the cockpit in accordance with the Coriolis acceleration (Fig. 2). For example, when the cockpit rolled right, the observer typically reported that he was rolling right, and in addition, that he was pitching down. For other observers, however, under the same conditions the report was a yawing motion of the cockpit either alone or in combination with the pitching motion. All of these effects were considered to be Coriolis effects. Therefore, the frequency of Coriolis effects was determined by two separate tallys. The first of these was made by simply counting the number of times roll was correctly reported in accordance with the added Coriolis acceleration during pitching maneuvers and similarly the number of times pitching was correctly reported during rolling maneuvers. The second tally was made by determining the number of times the observers reported either roll and/or yaw during pitching maneuvers and pitch and/or yaw during the rolling maneuvers.

The data were analyzed by pooling all of the pitch maneuvers and all of the roll maneuvers for all of the observers since there were no clear, consistent frequency differences between the various conditions. The results (Fig. 3) show, as would be predicted from earlier studies (e.g., Guedry and Montague[6] and Meda[7]), that the frequency of reports of Coriolis effects using both methods of determining the effects increases as a function of the velocity of rotation of simulator. The results are very similar for pitch and roll for both methods of counting the effects. The number of reports of roll during pitching maneuvers and pitch during rolling maneuvers falls far short of the maximum possible score for the lower angular velocities. The counts including reports of yaw, however, closely approach the total trials (224) at 12 rpm. Four observers (A, B, C, F) including one pilot (C), reported Coriolis

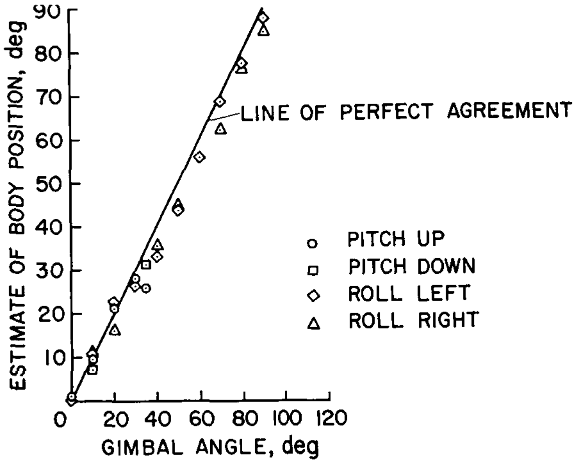


Fig. 5. Comparison of mean body position estimates with gimbal angle for seven observers (static observations).

ed no symptoms whatsoever during his regular runs when he was not taking the drug. These observations suggest that motion sickness would not be expected under these experimental conditions.

B. *Estimates of body position.*

Before the observations during rotation were begun, the observers were randomly placed in a series of pitches and banks and asked to estimate their body position. The data for up and down and left and right were combined to determine the mean performance

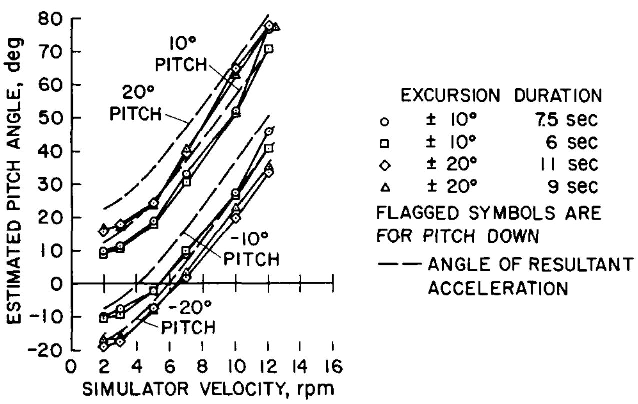


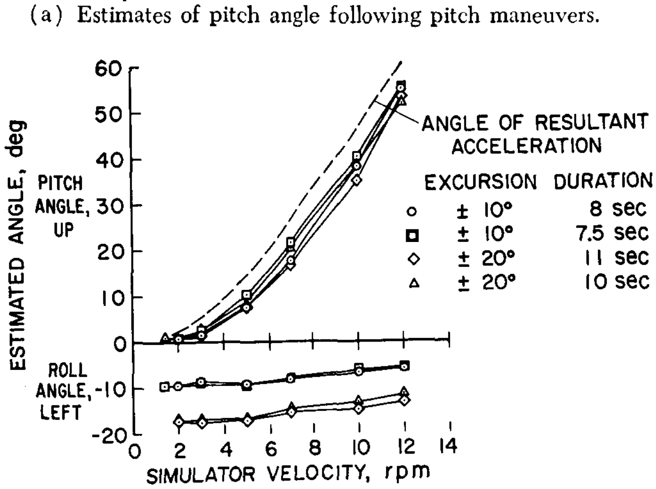
Fig. 6. Variation of mean body position estimates with simulator velocity for seven observers.
(a) Estimates of pitch angle following pitch maneuvers.

(Fig. 5). The results show that, for pitches and banks up to 20°, the estimates are very close to the true pitch or bank. Beyond 20°, however, there was a consistent tendency to underestimate the pitch or bank some 2-6°.

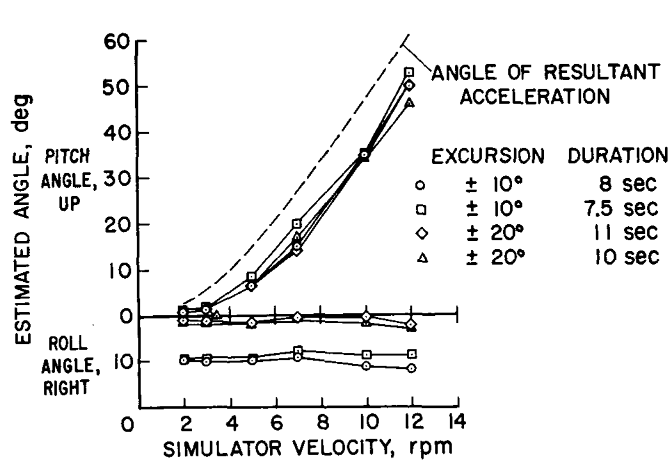
The observers' estimates of body position during rotation while pitched up or down also showed a tendency to be less than the angle of pitch using the resultant force acting on the observer in the pitched position as a reference (Fig. 6a). This applies to both 10° and 20° of pitch. At the higher velocities, however, the mean estimate of pitch was very close to the angle between the observer and the direction of resultant force.

The estimates of body position following the roll maneuver were more complex because the roll produced a change in the direction of gravity on the body in one direction while the centrifugal force changed it in another. Thus, observers would report roll to the right and pitch-up (Figs. 6b and 6c). The observers reported these estimates separately in degrees. The results are similar to those for pitch. At both 10° and 20° of bank the observers estimated the bank quite accurately, but as the velocity of rotation increased there was an increasing tendency to underestimate the roll. The estimates of pitch-up when the observers were rolled to the right or left gave results quite close to those during pitch when the direction of resultant force was used as a reference. The observers tended to estimate pitch-up at less than the angle between their body axis and the direction of resultant force. The underestimation was small at 2 rpm, increased at 3 rpm, and was less again at 12 rpm (Figs. 6b and 6c).

In general, these results suggest that within the range of conditions studied here, the observers tend to judge their body position with respect to the direction of resultant force acting on the body. The judgments tend to be somewhat less than the angle between the body axis and the direction of resultant force until the resultant force was about 1.8 g at which time the estimates are quite close to the angle between the resultant force and the observer's body. Furthermore, the data support the notion that stimulation of the semicircular canals by Coriolis forces has little, if any, effect on subsequent judgments of the postural vertical as estimated here.



(b) Estimates of pitch and roll angle following left roll maneuvers.



(c) Estimates of pitch and roll angle following right roll maneuvers.

DISCUSSION

These data on the subjective Coriolis reaction involving the perception of apparent bodily rotation are in general agreement with the findings of other investigators who have reported that for a *first approximation*, the semicircular canal system behaves very like a heavily damped torsion swing. The results for the duration of the subjective Coriolis reaction would have been predicted on the basis of the effective Coriolis couples acting on the semicircular canals[5,6] (Fig. 2) and are clearly a function of the velocity of rotation of the simulator and the duration of the cockpit maneuver within the limits of the conditions studied. At the same time the data give additional evidence supporting Groen's[5] notion that the transducer mechanism of the peripheral sense organ cannot explain perfectly all of the phenomena associated with stimulation by angular acceleration. Groen has noted that the central nervous system plays a key role in determining these effects. These data also make it clear that cockpit maneuvers in a rotating flight simulator can produce unusable motion cues which last well beyond the duration of the maneuver itself. These subjective Coriolis reactions began at 2 rpm in this simulator and lasted well over 30 seconds for one of the pilots at the higher velocities. These results can be reasonably generalized to other situations involving relatively prolonged cockpit maneuvers in a rotating environment.

The increase in the frequency of the subjective Coriolis reaction (Fig. 3) is completely in accord with the expectation that as stimuli increase in intensity and duration from values near threshold to values well above threshold, the effects will increase. Similarly, the increase in the duration of the subjective Coriolis reactions would be predicted on the basis of a single Coriolis acceleration pulse of increasing intensity. It should be noted that while the duration of the motion reported at 2 rpm was very close to the actual duration of the cockpit maneuver, even at this low velocity the duration of the reported motion tended to be longer than the cockpit maneuver (Fig. 4). Beyond 2 rpm the duration of the reported motion became increasingly greater than the duration of the cockpit maneuver. This increase can be attributed primarily to the effects of the Coriolis acceleration on the semicircular canals. It is clear, however, that the reported motion is for the most part a combination of the effects of the forces resulting from the direct effects of the maneuver itself plus the added effects of the Coriolis couple on the semicircular canals. In this respect, it is clear that these results would not be expected to be identical with the results of experiments involving head nodding. Some of the observers spontaneously reported during the regular runs that they could readily distinguish the two aspects of the motion in temporal sequence. For example during pitch-down they would report pitch-down followed quickly by pitch in combination with roll left, and finally a roll left alone. These spontaneous reports were supported by a limited number of observations by one observer after the regular series was completed. On a series of several trials at different simulator velocities, he reported on pitch alone and then on other trials on roll alone. The results indicate that the reports of pitch alone were shorter than the duration of the cockpit maneuver as defined above and that the complex subjective Coriolis reaction tended to last well beyond the reports of pitch particularly for the greater simulator velocities. Similar results were found for the roll maneuvers. These observations suggest that the reported motion is a function of *both* otolith and semicircular canal stimulation.

Differences among the observers in the frequency and duration of the subjective Coriolis reaction involving apparent bodily rotation were quite clear (Table II). But the most striking illustration of the fact that the pilot's reports of apparent bodily motion cannot be perfectly predicted from equations describing the effects of the force environment acting on the semicircular canals is to be found in the reports of the direction of the reported motion. Whereas the most typical subjective Coriolis reaction was a pitch or roll, predictable on the basis of the Coriolis acceleration (Fig. 2), two of the observers regularly reported yaw as the predominant effect while other subjects reported yaw occasionally. Such atypical responses are not entirely surprising since Gray, et al.[2] have observed that a substantial number of inconsistencies were reported by their subjects for visual Coriolis reactions. The reports by the observers in the present study would suggest that end organ effects could not completely explain the phenomena reported, and that one should look to central nervous system effects as suggested by Groen.[5] Gray and his colleagues suggested that inconsistencies were merely errors in reporting. Such an explanation is, of course, always a possibility, but the repeated reports of yaw by two of our observers could hardly be simple errors in reporting. They were too numerous and too consistent. It is suggested that one causal factor is a unique frame of reference of the particular observer. For example, two of the observers reported that when apparent motion had ceased after a trial, they perceived that the nose of the cockpit was yawed out of position 10-15°. Another observer reported regularly that the cockpit was "swinging out" away from the center of rotation of the simulator. Another possible factor is the influence of higher order effects associated with the force environment acting on the observer. A third possibility of a causal effect in this particular simulator is the great complexity of the stimulus flux acting on the observer and the interaction of these effects which were sometime disparate. The semicircular canals were stimulated by both the rotation of the cockpit and by the Coriolis accelerations. There were unique otolith cues resulting from the position of the cockpit and the increase in resultant force. The latter cues also stimulated other proprioceptive and tactual receptors. It may be that the two atypical observers were more sensitive to higher order variables or they may have been less sensitive to primary effects and found it easier to report secondary effects.

A final point may be made in connection with a comparison of the reports of the pilots and nonpilots. With only two pilots and five nonpilots, far reaching generalizations are impossible. Nevertheless, it can be pointed out that the pilots did not appear to constitute a special group. With regard to frequency of response, one pilot fell in the largest group and the other pilot in the group with less frequent reports. A similar statement applies to the duration of the effects, but one pilot consistently reported by far the longest duration of apparent motion. Again, with respect to the direction of reported motion, one pilot gave reports similar to those predicted on the basis of the Coriolis force, while the other pilot gave atypical responses. Thus, the pilots appeared to give no responses which distinguished them from the non-pilots.

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